Overview of the State-of-the-Practice in Liquid Propellant Rocket Engine Design, Analysis, and Test

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Agenda

- **Overview of the Space Transportation Market, Current Space Vehicles and Propulsion Systems**

- **Challenges in Liquid-Propellant Rocket Engine Development and Future Direction**

- **Video on the Current State-of-the-Practice in Rocket Engine Turbine Blade Design and Analysis (18 min.)**

- **Key Rocket Engine Components, Examples of Current Engineering Practices, Technology Needs for the Future**
  - Rotating Machinery
  - Thrust Chamber Assembly
  - Propellant Feed Systems

- **Conclusions and Some Thoughts on University, Government and Industry Collaboration**

Overview of the Space Transportation Market, Current Space Vehicles and Propulsion Systems

Current View of the Space Transportation Markets

Market Outlook

- **Defense**
  - National Missile Defense
  - Integrated Battle Space Management
  - Military Aerospace Plane

Strong growth
(Tied to DOD budget)

- **Science**
  - International Space Station
  - Space Exploration
  - Space Launch Initiative

Slow growth
(Tied to NASA budget)

- **Commercial**
  - Communication satellites
  - Global connectivity
  - Space-based communication systems

Flat
(supply > demand)

Future is Bright

The Space Transportation Field is Now Global

Current Vehicles

Expendable – Non-man-rated

1993

Atlas
(Lockheed)

1987

Titan IV
(Lockheed)

1989

1996

2002

Delta II, III, IV
(Boeing)

1990

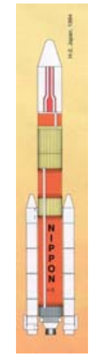
Long March
(China)

1988

1996

Ariane IV & V
(Europe)

1994



H-2
(Japan)

1985

Zenit
(Russia)

Expendable – Man-rated

1965

Proton
(Russia)

Reusable – Man-rated

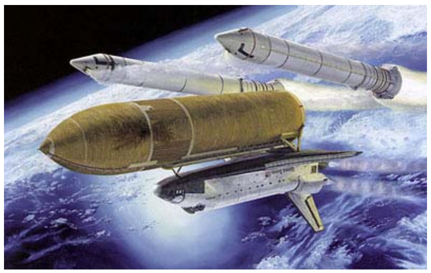
1981

Space Shuttle
(Boeing)

Rocket Based Propulsion System Types

Pure Rocket Systems

Gas Generator **Staged-Combustion**

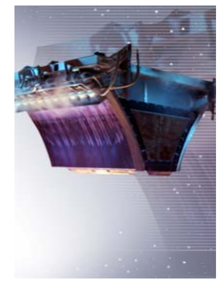


Shuttle SRBs

Atlas

Delta

SSME



Linear Aerospike Engine

Solid Propellant
(NH_4ClO_4, CTPB, Al)

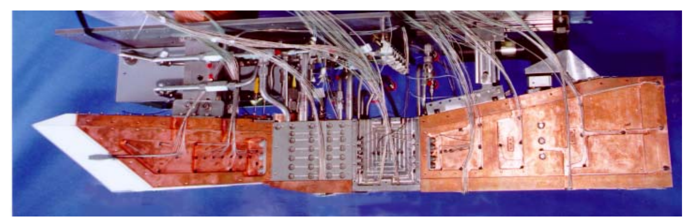
Liquid Propellant
(H_2, RP1, H_2O_2)

Advanced Concepts
(Aerospike, Nuclear, Ion, Plasma)

Hybrid Engines

Combination of Solid & Liquid Propellant Engines

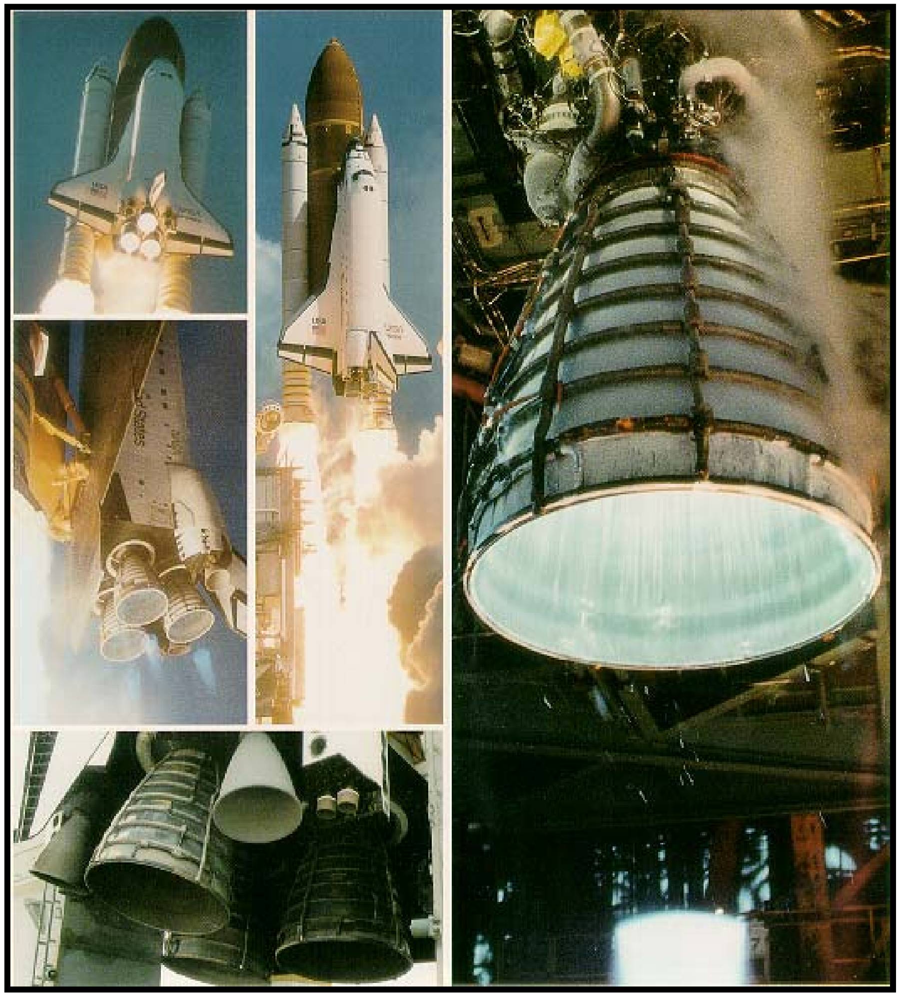
Combined Cycle Engines



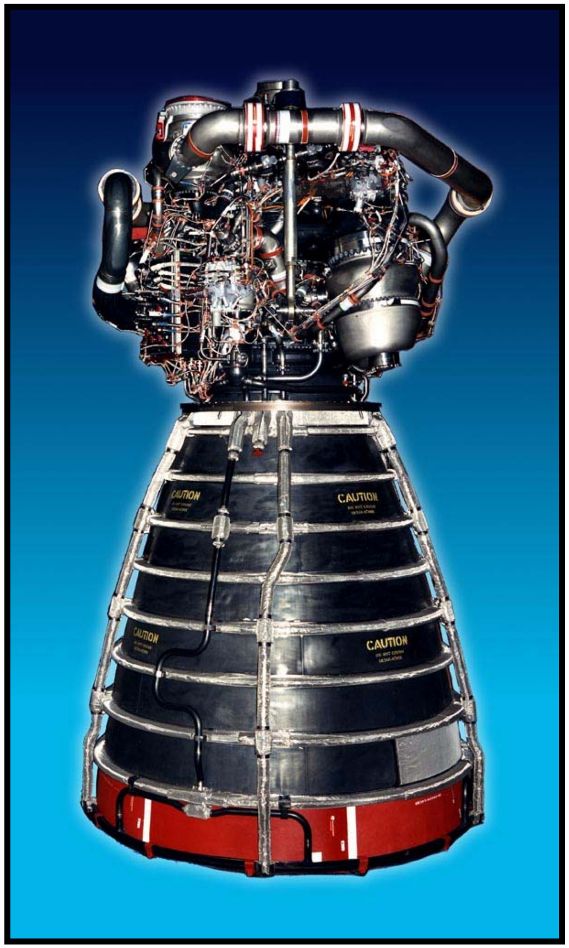
Combination of Airbreathing & Liquid Propellant Rocket Engines

Some Facts on the Space Shuttle Main Engine

- 3 main engines operate for 8 1/2 minutes during ascent
- Sole source of propulsion once the Solid Rocket Motors are separated at T +120 seconds
- Engine is the first large reusable LOX / Hydrogen engine
- Engines have performed safely for all 109 launches
- Continuous improvements have made the engines safer to operate and easier to maintain



Rocket Engines Deliver Tremendous Power in a Small Package



14 Feet High

7.5 Feet Wide

Space Shuttle Main Engine (SSME)

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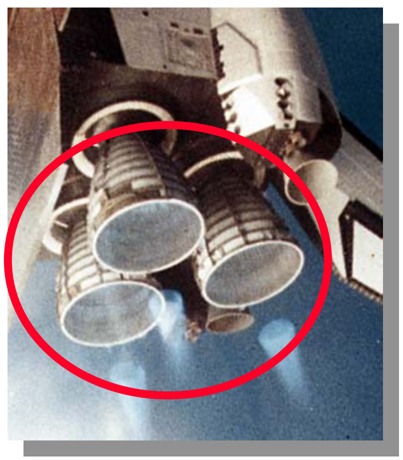
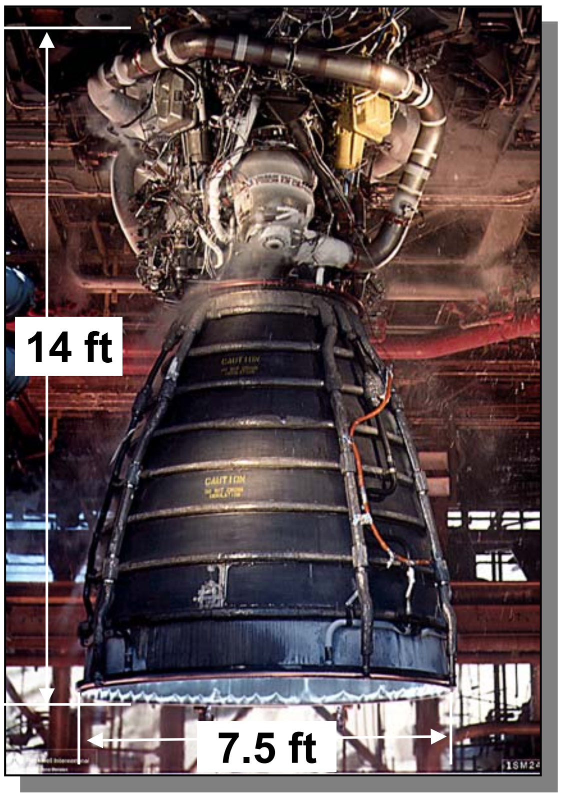
The energy released by three of Space Shuttle Main Engines is equivalent to the output of 23 Hoover Dams



37 Million Horsepower!

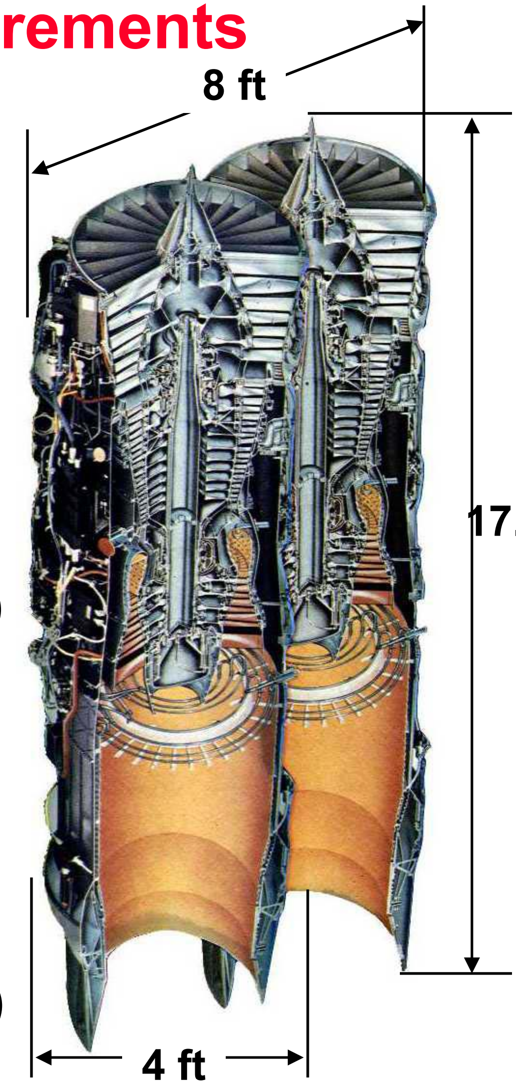
Rocket Propulsion Systems Place Greater Demands on the Hardware

Leads to more stringent requirements



Weight 7,748 lb
SSME

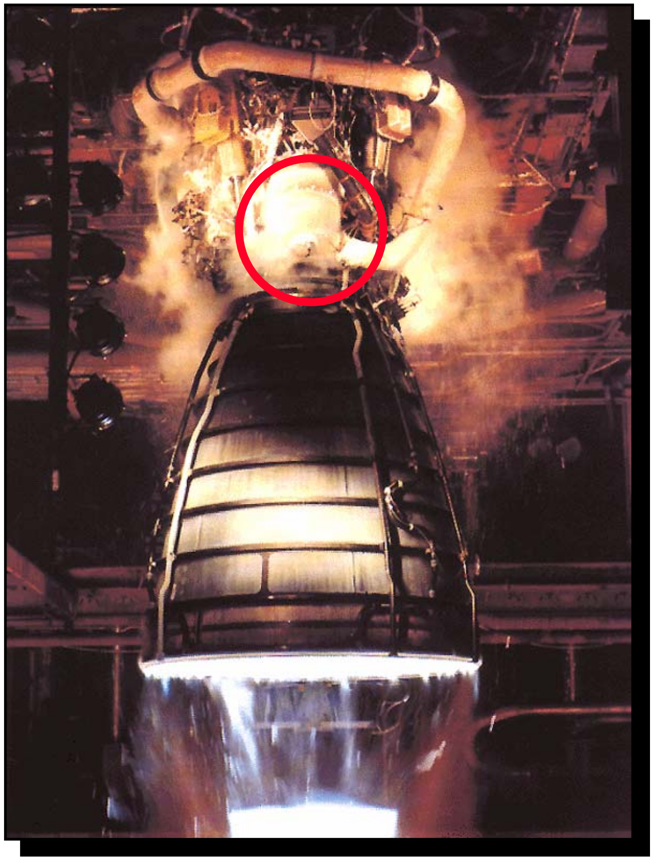
500,000 lb
Thrust



Weight 7,300 lb (2)
Turbojet Engine
(2 ea on F-15)

50,000 lb (2)
Thrust
Full After Burner

Rocket Propulsion Systems Place Greater Demands on the Hardware



High Pressure Fuel Turbopump

- The SSME High Pressure Fuel Turbopump (HPFTP) alone delivers as much horsepower as 28 locomotives

- The HPFTP generates 70 hp per pound while an aircraft engine generates 3 hp per pound

70 Horsepower per pound

VS

3 Horsepower Per Pound

Rocket Engines Operate in Very Hostile & Unforgiving Environments

- SSME operates at greater temperature extremes than any mechanical system in common use today (except nuclear reactors)
- Hydrogen fuel at - 423° F is the second coldest liquid on Earth
- Combustion chamber reaches +6000° F hotter than the boiling point of Iron

Attention to Every Detail Is a Essential for Rocket Engines

Challenges

in Liquid-Propellant Rocket Engine

Development and Future Direction

New Rocket Engine Development Programs Face Many Challenges

- New engine development is expensive and requires multi-year commitment
- Product integrity and performance can not be comprised in any way – especially in human flight
- However cost needs to be considered as an independent variable to establish the business case (go, no-go decision on the program)
- The design process is still a mix of engineering, science, experience, & art
- Since the SSMEs there has been no new flight engine development for a quarter of a century until the RS-68 engine (scheduled to fly this August)

Critical Issues in Rocket Engine Development
Technical

- **System level design and analysis capability**
  - Component level (e.g. turbopump) vs sub-component level design (e.g. impeller) considerations - entire engine being the ultimate goal
  - Fast enough to enable tradeoffs early in the design cycle
- **Efficient and accurate simulation of dynamic flow phenomena and loads**
  - Start-up and shut-down transients
  - Nozzle side loads, structural response to off-design loads
  - Instabilities (combustion and flow driven)
- **Quantification of risk and uncertainty**
  - Tool validation/verification/calibration issues
  - Scarcity of benchmark quality data
  - Limited success in modeling key phenomena (e.g. turbulence)

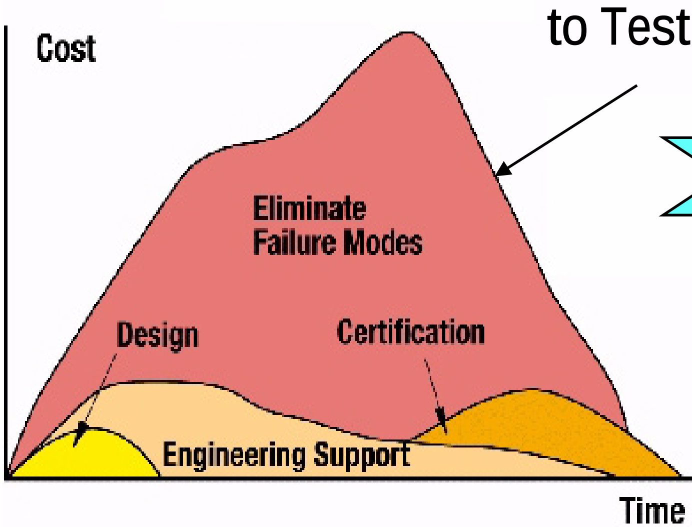
Critical Issues in Rocket Engine Development

Other

- **Experience base diminishing**
  - Current SOP blends experience, new tools, art and science
  - Experienced resident with key people retired or about to retire
  - Knowledge capture not progressing fast enough
- **Less testing, more modeling**
  - Cost considerations significantly reduce development testing
  - Programs assume first time success
  - No margin for error
- **Rocket propulsion industry is changing**
  - Driven more by the commercial market (fixed cost deals)
  - Global competition
  - Significant investment of Company resources required to stay competitive

To Meet the Challenges of the New Environment, We Need to Change our Practices

History

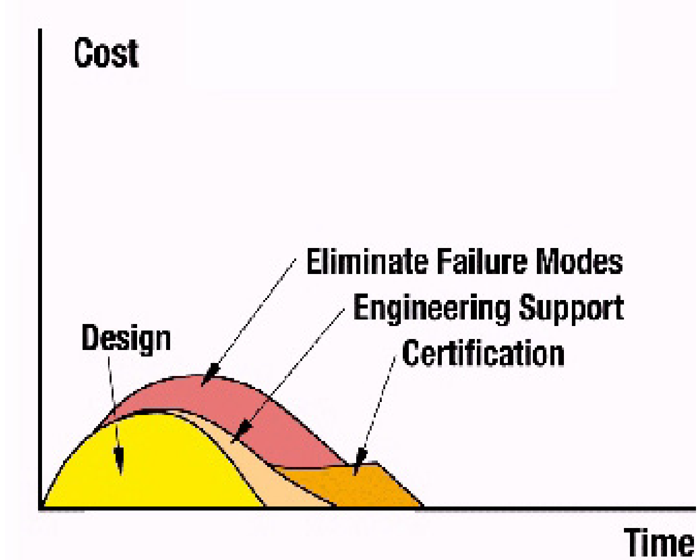


73% of program cost related to Test-Fail-Fix cycle

New Processes

Concurrent Engineering & Robust Design Practices

Where We Need to be



- Streamline design, analysis, & test processes
- Identify all possible failure modes early
- Fully explore the design space
- Account for variabilities
- Quantify risks, sensitivities, margins, system & component reliability

Target Goals

Reduce Development Cost by a Factor of *10*

Reduce Development Time by a Factor of *4*

Reduce Cost of Payload To Orbit by a Factor of *100* (~$100/lb)

New Processes are Changing the Traditional Design & Analysis Practices

- **Boundaries between design phases are shifting**
  - High fidelity analysis is being pushed earlier into the design cycle due to increased computer speeds and automation
  - Tools from detailed design (3-D CFD and FEM stress) are now being used in preliminary design
  - Preliminary design cycle times for some disciplines are approaching conceptual design cycle times
- **More demands are being placed on system level tools**
  - Operate in scalable heterogeneous computing environments
  - Control expensive analysis codes
  - Support optimization techniques utilizing more variables
  - Guide multiple disciplines

One Approach to Concurrent Engineering

Concurrent Engineering System

- Streamline, Standardize and Automate Current Analysis Processes
- Introduce Robust Design Concepts & Practices
- Establish Computational Framework for Multidisciplinary Analysis and Optimization

Video (18 min.)

1. **Current State-of-the-Practice in Rocket Engine Turbine Blade Design & Analysis**
2. **Use of Advanced Technology Examples**
   - International Space Station
   - Delta IV – RS-68 Engine Development
3. **The Analysis Vision for the Future**

Key Rocket Engine Components, Examples of Current Engineering Practices, Technology Needs for the Future

- Rotating Machinery
- Thrust Chamber Assembly
- Propellant Feed Systems

Typical Liquid-Propellant Rocket Engine Major Subsystems

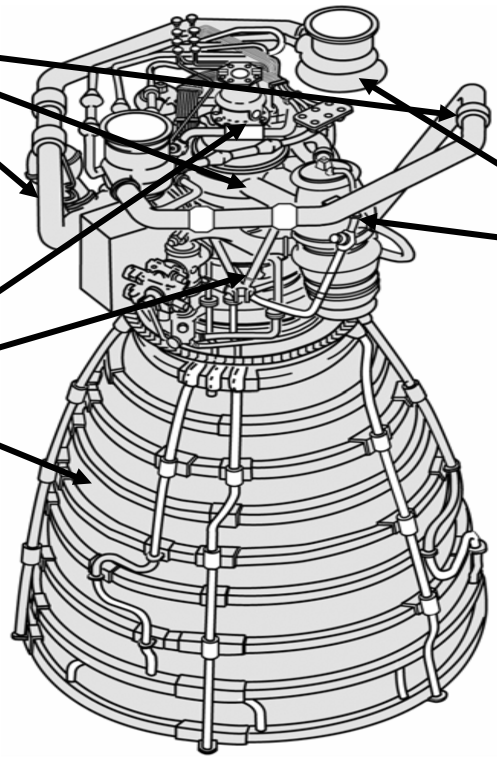
Staged Combustion Engine Cycle (e.g. Space Shuttle Main Engines)

Propellant Feed System

- Manifolds
- Ducts
- Valves

Thrust Chamber

- Preburners
- Main injector
- Combustion chamber
- Nozzle



Rotating Machinery

- Turbopumps
  (high & low pressure)

New Engine Development Cycle

Conceptual Design ~ 2-4 months

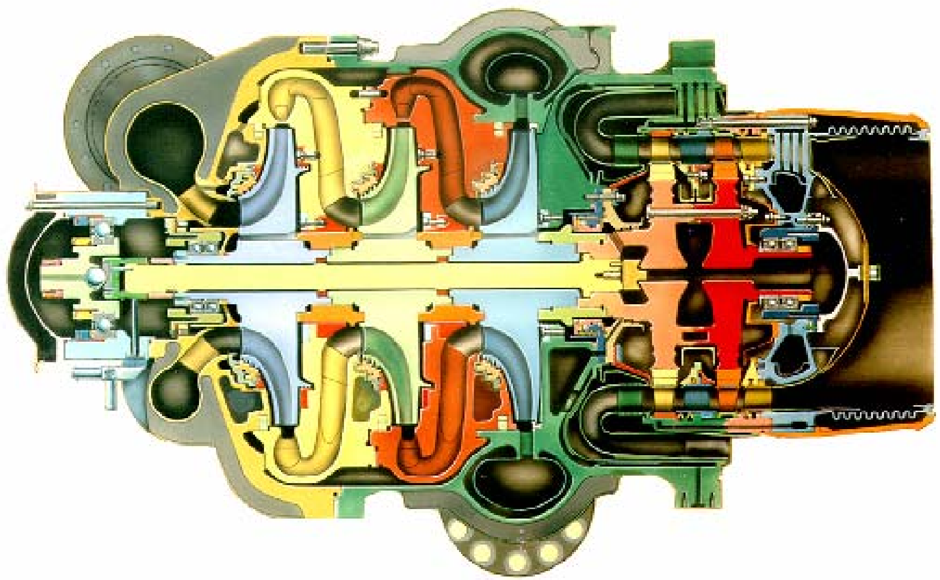
Preliminary Design ~ 6-8 months

Detailed Design ~ 12-14 months

Rotating Machinery

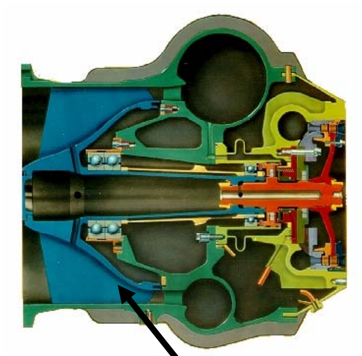
Rotating Machinery

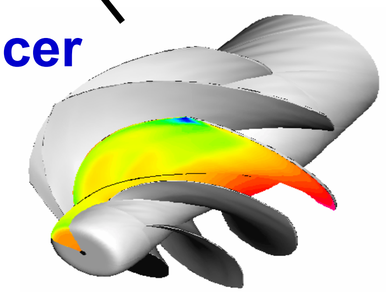
Typical Turbopump Cross-section (SSME HPFTP)



Rocket engine rotating machinery generally consist of pumps driven by turbines (turbopumps). The function of the turbopump is to receive the liquid propellants from the vehicle tanks at low pressure and deliver them to the combustion chamber at the required flow rate and injection pressure.

Key Turbopump Sub-components



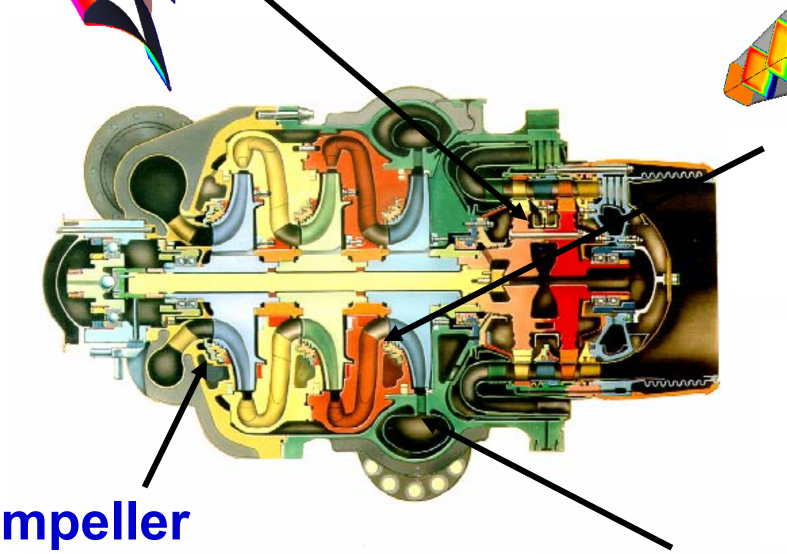


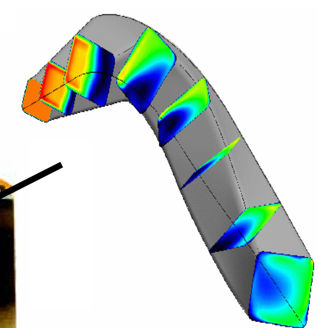
Inducer

The axial inlet portion of the turbopump rotor whose function is to raise the inlet head by a amount sufficient to preclude cavitation in the following stage

Turbine Blade Cascade

Blade cascade that provides the power to drive the pump

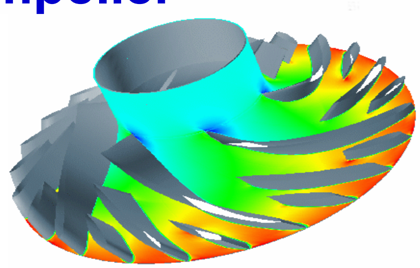




Crossover Duct

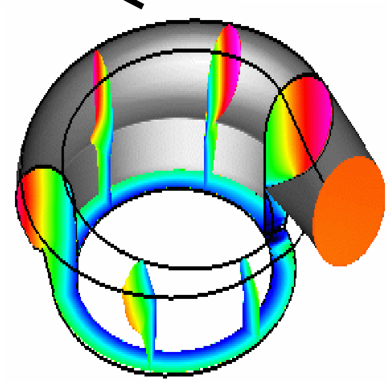
Stationary elements that convert kinetic energy imparted on the fluid by the rotating components to the static pressure as well as provide the correct flow angles to the downstream elements

Impeller



Centrifugal flow devices that change the flow direction from axial to radial and impart kinetic energy by doing work on the fluid

Volute



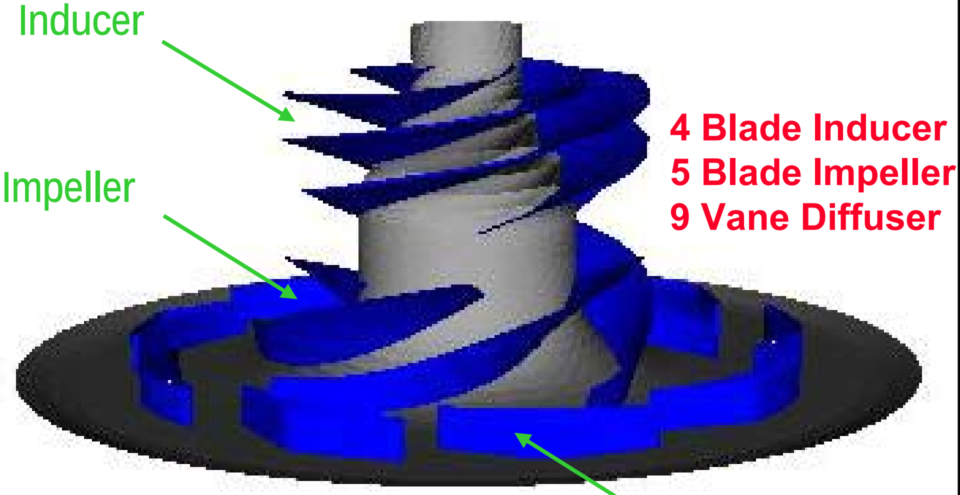
Scroll type devices required to capture the flow out of the turbopump stages and direct it into the downstream piping system

Digital Turbopump Results Enable Timely Anomaly Resolution

Featuring eTango & Enigma CFD

- **Coupled (inducer+impeller+diffuser) unsteady CFD analysis used to resolve bearing failure issues in turbopump**
- **Analysis provides load history that help explain rubbing and uneven load distribution observed on test element**

Coupled Unsteady Analysis - Inducer+Impeller+Diffuser



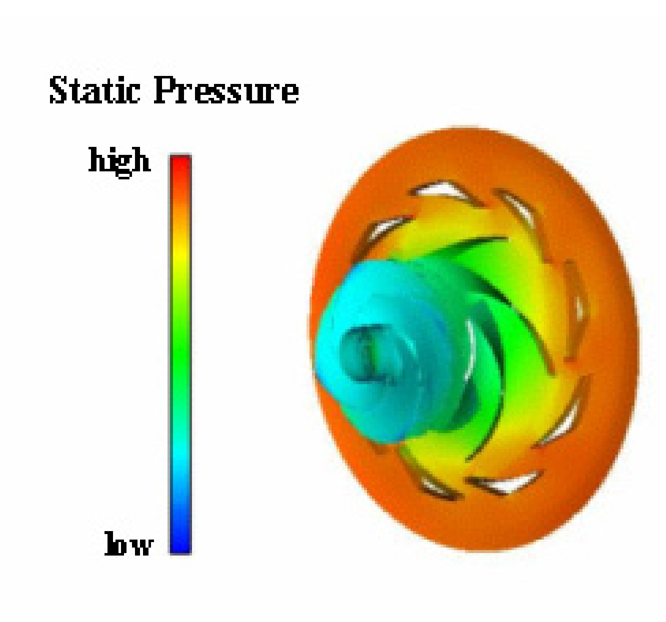
- 244K node model
- ~ 6 hour set up time
  - 1 hour for inducer grid
  - 2 minutes for impeller grid
  - 4 hours for diffuser grid
  - 1 hour to build coupled model inducer+impeller+diffuser using Multi-Device-Snap-Together technology (being patented)
- 3 day run time on single 933 mhz PC

Time step = 1.90346e-5 seconds

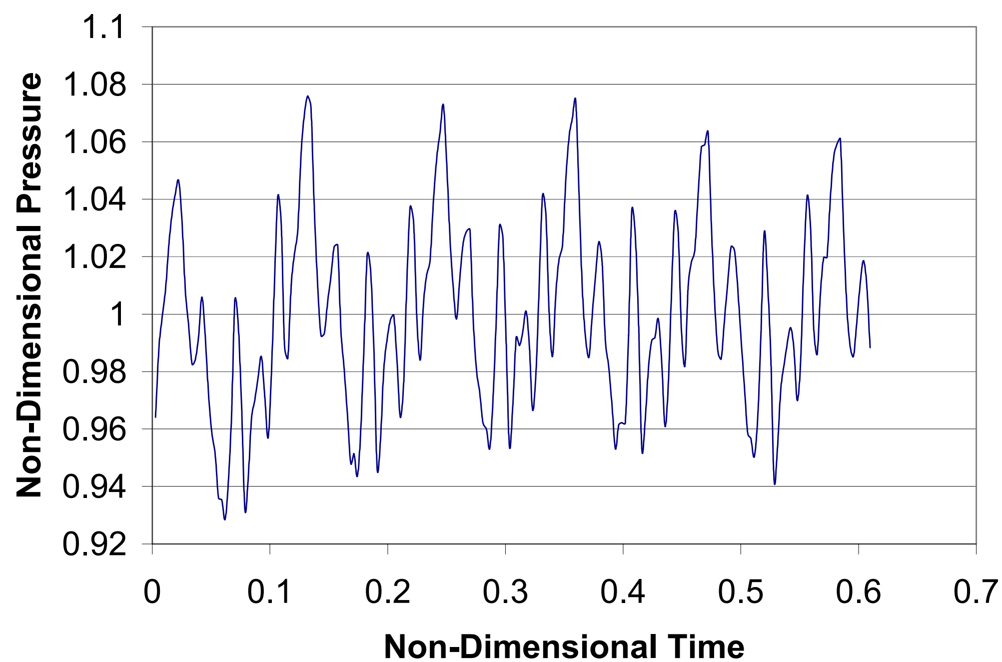
- Resolved frequencies (Nyquist freq)=26,268 Hz
- Impeller grid moves 1 deg (0.01745 rad) each time step

Impeller Blade Tip Fluctuating Static Pressure

- CFD predictions used to bracket the amount of alternating torque being transmitted to the pump end bearing at different power levels
- Subsequent stress analysis (using the calculated alternating torque levels) showed sufficient bearing life
- Analysis saved $1.5M which is the cost doing a flow test to measure the alternating torque

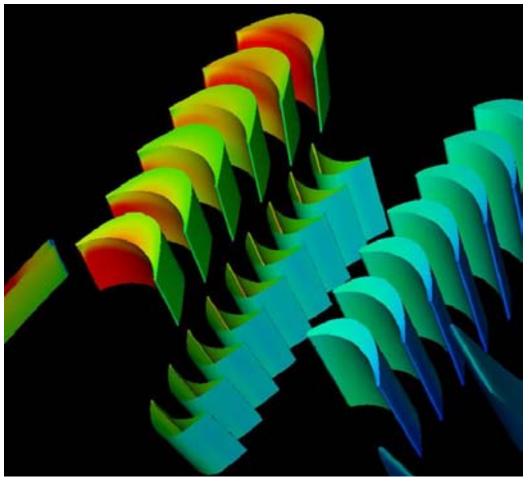


Static Pressure at Non-D Time=0.319

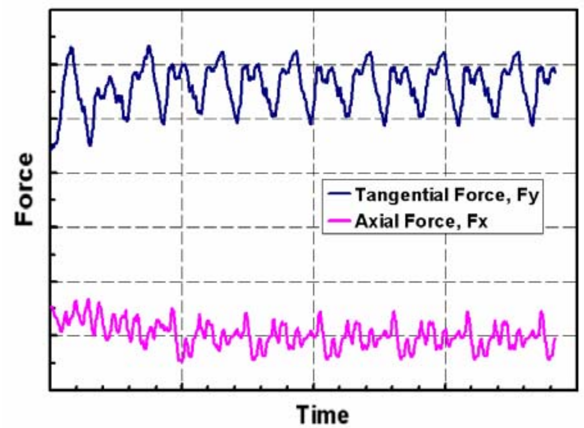


High Power Level, Nominal Q/N

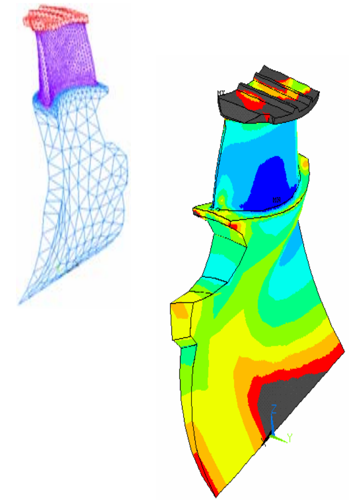
Integrated Fluid-Structure Analysis Tools to Enable Better First Time Turbine Design



3-D CFD Solution



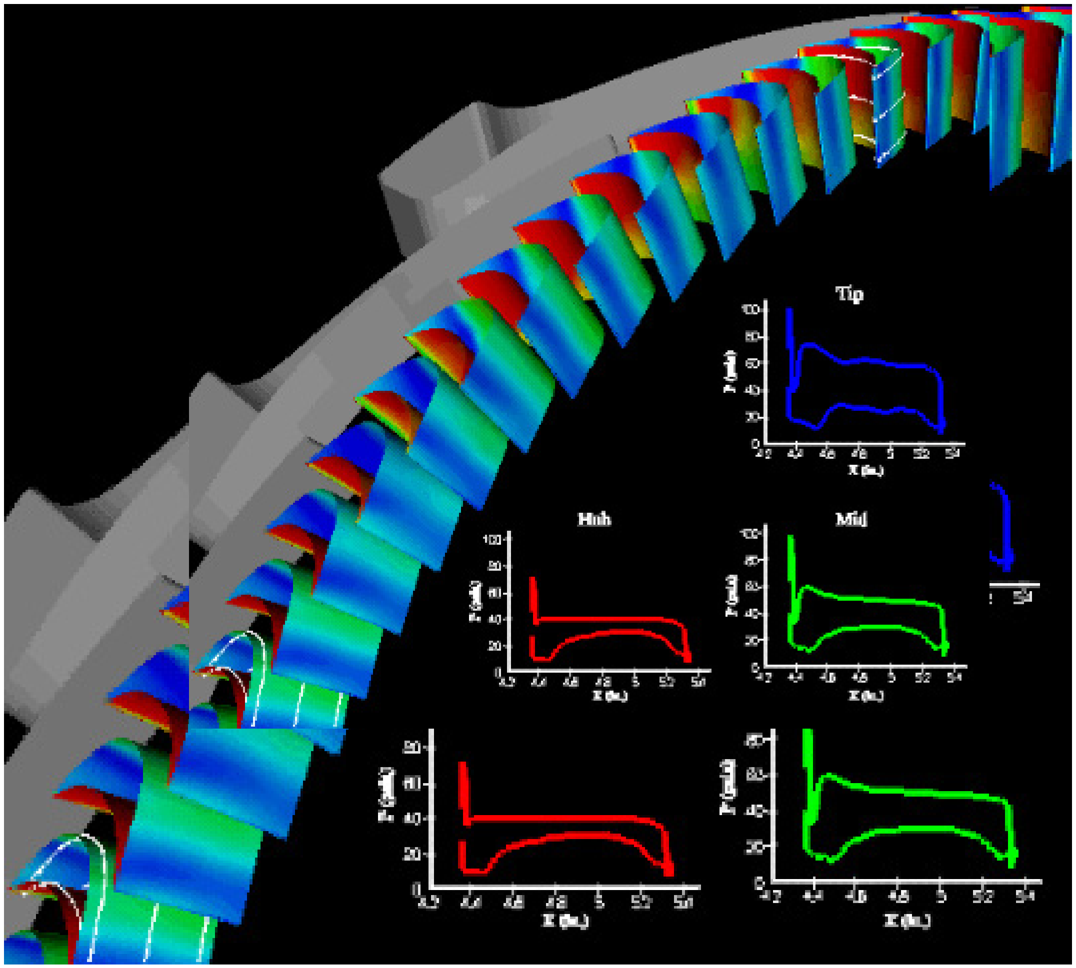
Unsteady Blade Loading



Applied to Structure

- **Turbine Life Enhancement IAD develops tools for dynamic environment prediction (CFD) and turbine response analysis (Structural Dynamics)**
  - **3-D unsteady CFD tools define turbine blades dynamic load environment**
  - **In-house turbine test data used for CFD code validation**
  - **Unsteady CFD-based loads applied to predict turbine blade dynamic response**
- **Substantial analysis cycle time reductions achieved (e.g., 10-100X)**
- **Potential cost avoidance: $10M/anomaly (historical data, RS-68)**

Simulations Show High Dynamic Loads on the Turbine Blades & Disk that Need to be Damped



Turbopump Engineering Challenges & Technology Needs (1/2)

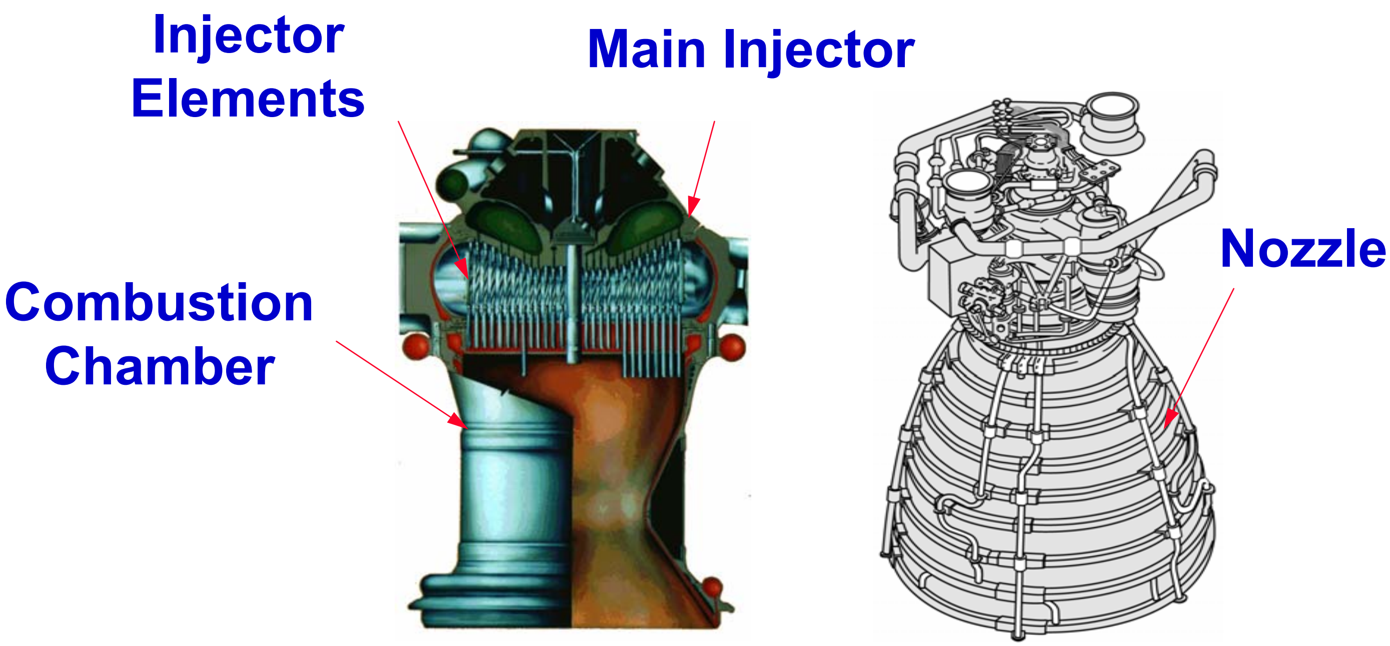
- **Rotating machinery flows are among the most complex internal flows**
  - 3D, large regions of separation, strong flow non-uniformities
  - May contain incompressible, subsonic, transonic and even supersonic flows within the same turbopump
  - High speeds of rotation (e.g. 38,000 RPM for the SSME HPFTP) create a highly turbulent, and strongly anisotropic flow dominated by vortical motions, separated boundary layers and vortex shedding
  - Multiphase flows (cavitation in inducers and liquid-gas mixtures around some types of bearings) are also observed
  - Extremely high dynamic loads and thermal gradients (e.g. temperatures change by ~ 2000^{o} R within a few inches)

Turbopump Engineering Challenges & Technology Needs (2/2)

- **Engineering challenges and technology needs include**
  - Ability to rapidly predict the flow and thermal environment in the entire turbopump (a CFD challenge – dynamic grid adaptation; highly efficient solvers for 3D transient mixed flows; workable turbulence models; PC-based parallel computing capability (~ 1000 PCs); and large database management & postprocessing technologies)
  - Interfacing CFD predicted flow and thermal environments and loads with stress and structural dynamics codes and material databases to determine part thickness, yield and failure limits, and margins of safety (dual challenge – CFD has to provide what stress needs, stress has to understand CFD's limitations and areas of uncertainty)
  - Understanding turbine disk instability mechanisms including acoustic excitation
  - Developing a user-friendly methodology to include secondary (thermal) stresses in fracture mechanics analysis
  - Acquiring quality test data and experiments to validate models and predictions

Thrust Chamber Assembly

Thrust Chamber Assembly

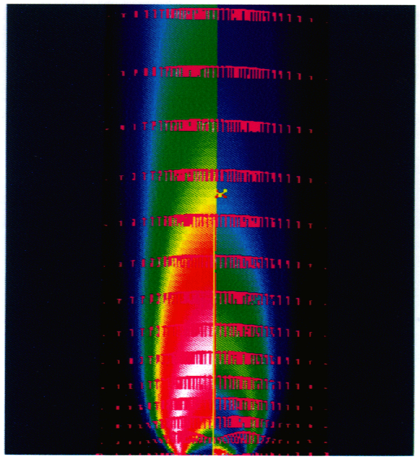


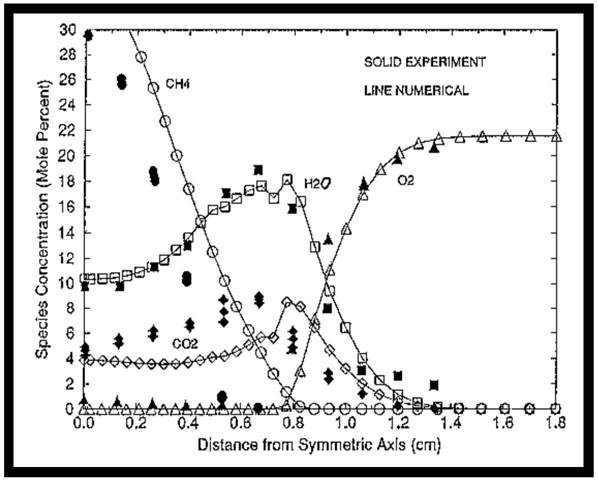
Thrust chamber assemblies consist of three major components: the injector,the combustion chamber, the nozzle. The injector delivers the fuel and oxidizer to the combustion chamber through gas-gas, gas-liquid, or liquid-gas injector elements. In the combustion chamber, the fuel and oxidizer are injected, vaporized (if necessary), mixed, ignited, and burned.   Once the propellants are combusted they can be expanded through a convergent-divergent nozzle producing thrust in the process.

CFD Tools Used in the Analysis of Injector Elements and Combustion Chambers

Methane Burner

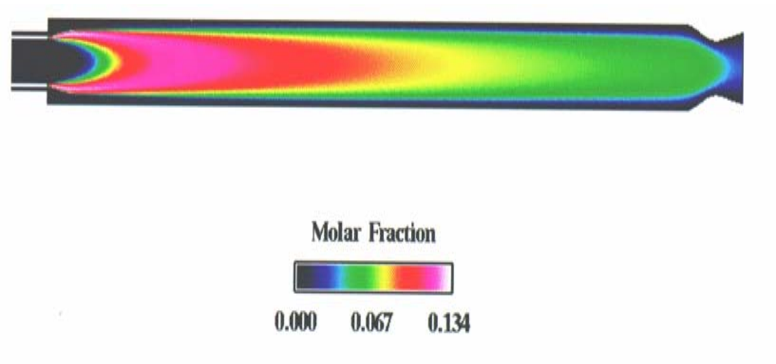
Temperature contours 275-2475 ^{0}K





Single Coaxial Injector Element

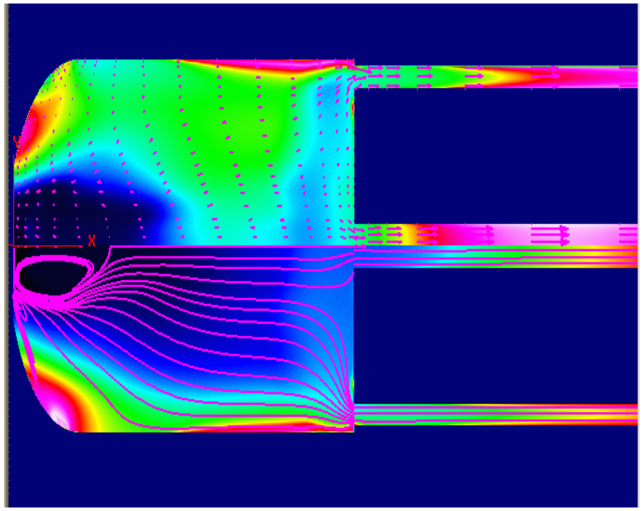
OH Concentration



Hybrid Engine Combustion Chamber

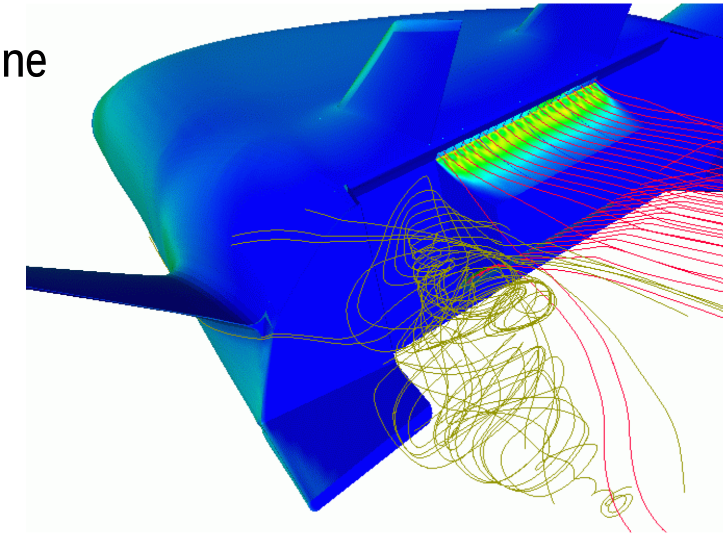
Temperature Contours & Velocity Vectors

H_2O Mole Fraction & Particle Traces

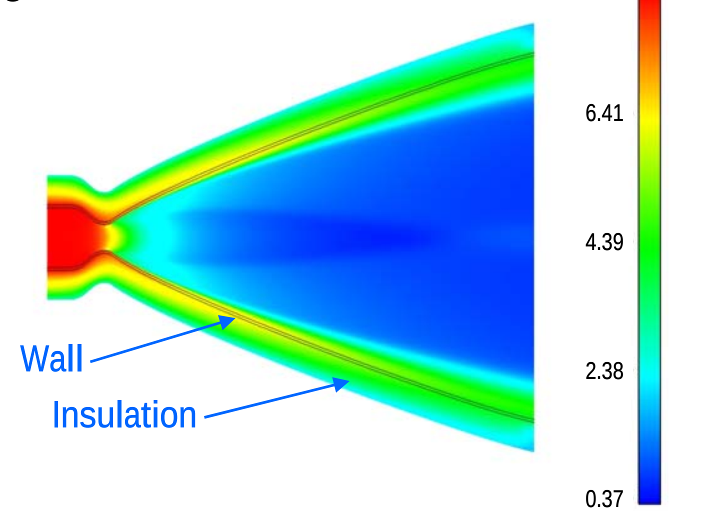


Nozzle Performance & Hardware Environment Defined

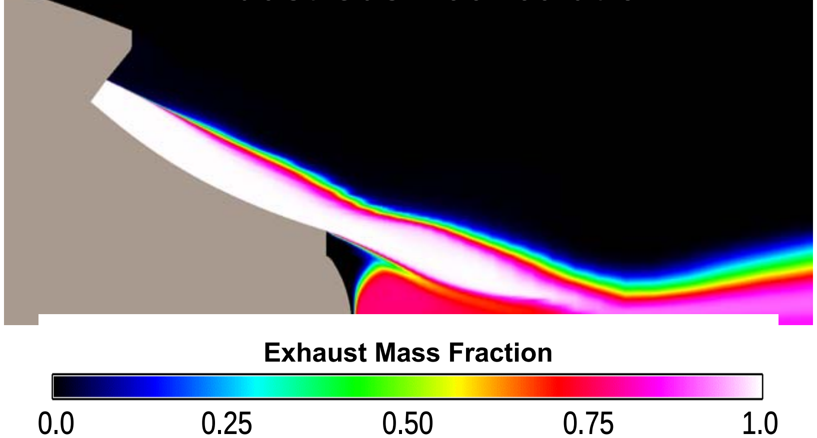
X-33 Vehicle-Engine Interactions



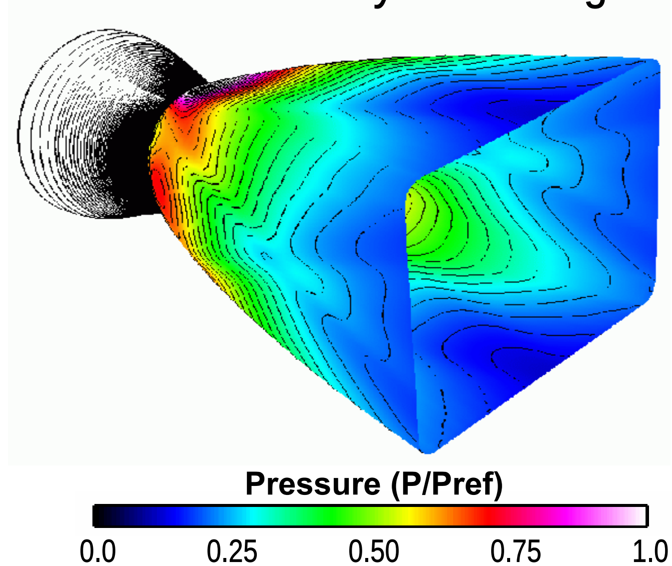
Conjugate Heat Transfer for SOTV



CFD Predicts Base Bleed Breakdown & Exhaust Gas Recirculation



3-D Thruster Analysis & Design



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Thrust Chamber Assembly Engineering Challenges & Technology Needs (1/2)

- **Rocket engine thrust chamber design provide many challenges**
    - Spray combustion process encompasses many physical processes of different types, temporal and spatial scales, tightly coupled to each other (two-phase mixing, combustion, turbulence, kinetics, instabilities) making environment definition and modeling very difficult
    - Extremely high heat loads require exotic materials and active cooling
    - Transient phenomena can lead to severe instabilities in the combustor and nozzle
    - Performance and durability issues require trade-offs and limit the design envelope
    - Test data are difficult and very expensive to obtain

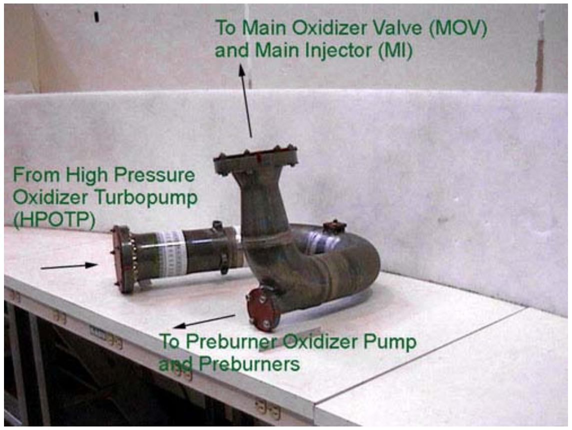
Thrust Chamber Assembly Engineering Challenges & Technology Needs (2/2)

- **Engineering challenges and technology needs include**
  - Ability to rapidly predict the flow and thermal environment in the combustion chamber (another CFD challenge – dynamic grid adaptation; highly efficient solvers for 3D transient mixed flows; workable turbulence models; mechanistic combustion models & correlations; PC-based parallel computing capability (~ 1000 PCs); and large database management & postprocessing technologies)
  - Interfacing CFD predicted flow and thermal environments and loads with stress and structural dynamics codes and material databases to select materials and coatings, yield and failure limits, active cooling requirements, and margins of safety (triple challenge – CFD has to provide what material scientists and stress engineers need, and they have to understand CFD's limitations and areas of uncertainty)
  - Chamber durability and injector performance
  - Combustion stability especially with hydrocarbon based fuels
  - Acquiring quality test data and experiments to validate models and predictions

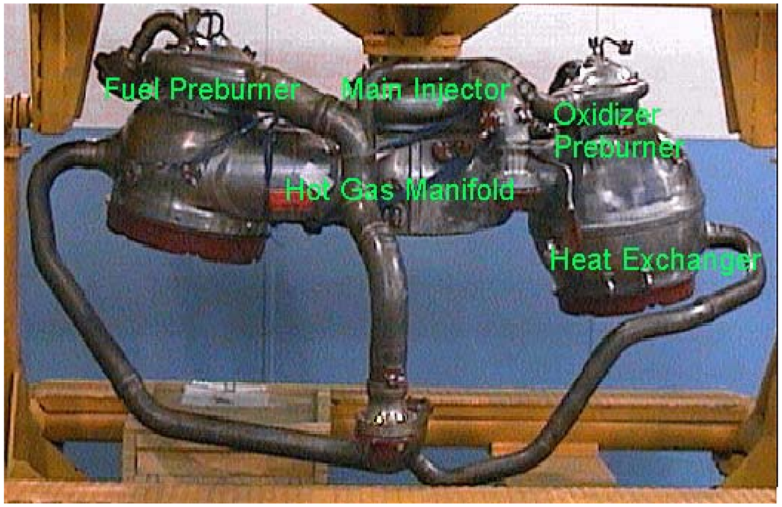
Propellant Feed System

Propellant Feed System

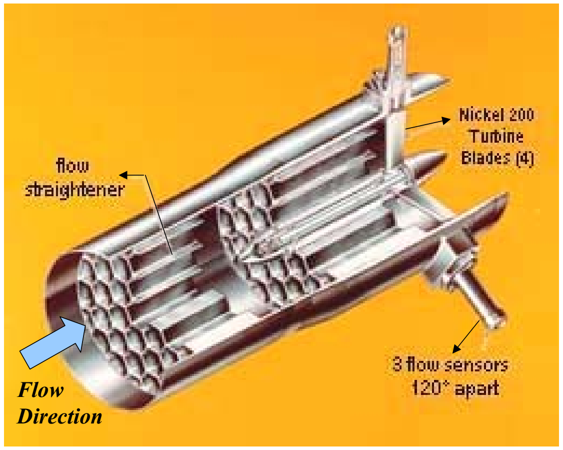
Typical Valves



SSME Hot Gas Manifold (HGM)



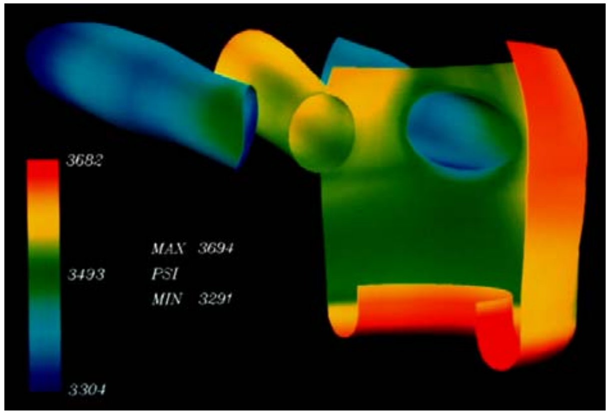
Fuel Flowmeter



Propellant Feed System is an assembly of ducts, valves, pipes, and manifolds that deliver the propellants to the turbopumps from the fuel and oxidizer tanks and then from the turbopumps to the combustion chamber.

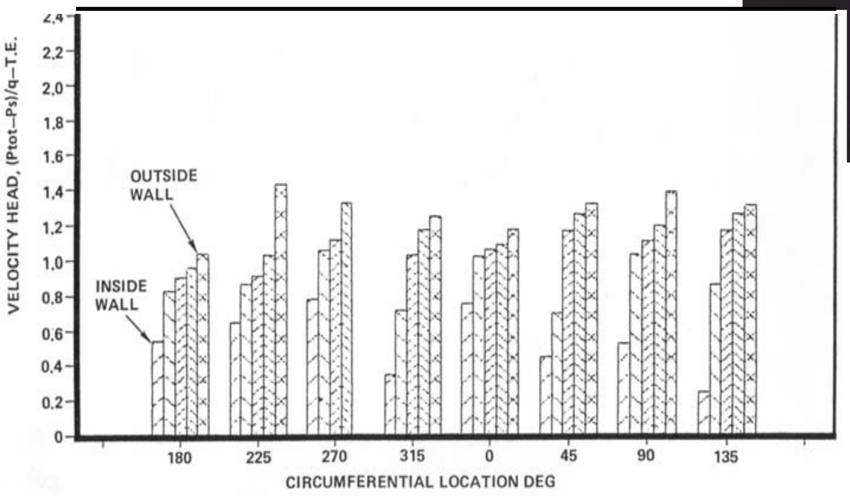
SSME Hot Gas Manifold Redesign Study

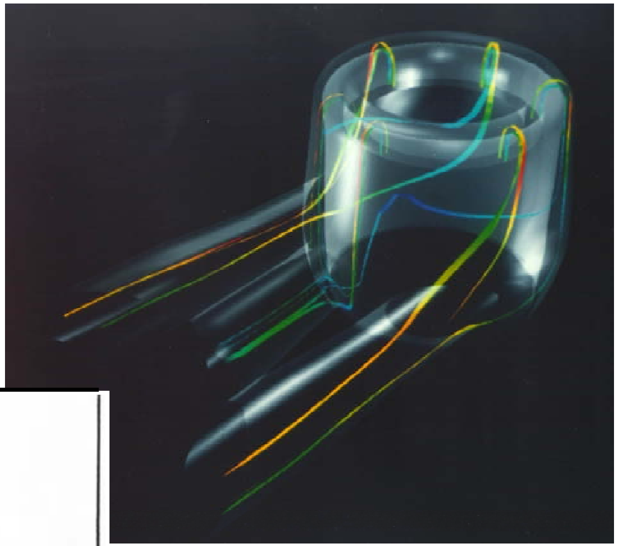
- **First major CFD effort undertaken in rocket engine design**
  - Collaborative effort between Rocketdyne & NASA (initiated in 1982)
  - Led to the development of the first engineering CFD code (INS3D) to be used in design guidance
- **Used on the redesign of the SSME HGM (fuel and oxidizer)**
  - Evaluated flow uniformity of proposed two-tube configuration (vs. three-tube)
  - Redesigned fuel bowl contour for reduced pressure losses
  - Designed and evaluated new inlet fairings



HGM Fuel Bowl-Pressure

Air Flow Test Results Verify Flow Uniformity of CFD-Based Design





HGM Fuel Bowl-Flow Ribbons

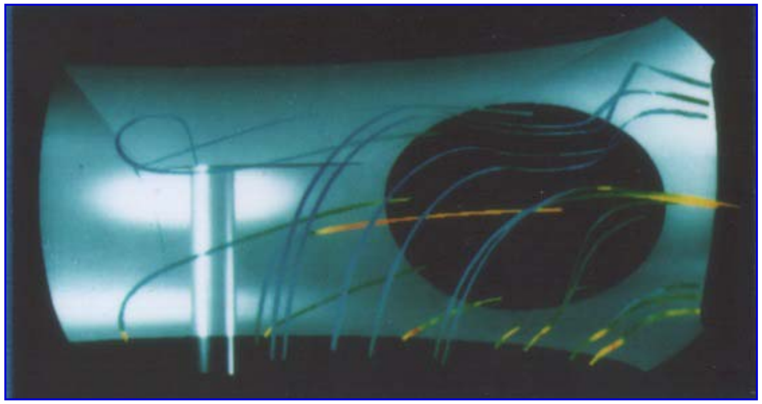
Canoga Park

BOEING

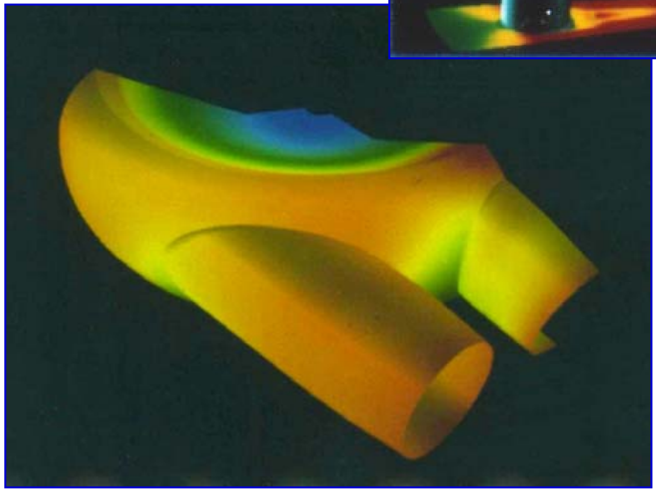
AA/??-0??-39/mms/??/??/??

SSME Main Injector Compatibility Study

- **Second part of the collaborative effort between Rocketdyne and NASA that led to the design of the Phase II HGM (the current flight engine)**
- **Focused on the effects of the new HGM design (two-tube) on main injector performance**
  - Evaluated the loads on the main injector for the old (three-tube) and new designs (two-tube)
  - Helped to assess the uniformity of flow entering main injector LOX post array



MI-Entrant Flow from Transfer Ducts



MI-Surface Pressures

Propellant Feed System Engineering Challenges & Technology Needs (1/2)

- **These are largely incompressible internal flows in complex geometries**
  - 3D, large regions of separation, strong flow non-uniformities
  - Strongly anisotropic flows dominated by vortical motions, separated boundary layers and vortex shedding
  - Two phase (liquid/gas) flows may occur in some valves
  - The challenge is to minimize the flow non-uniformities, total pressure drop, and the static & dynamic loads across the system
  - The goal is to minimize weight

Propellant Feed System Engineering Challenges & Technology Needs (2/2)

- **Engineering challenges and technology needs include**
  - Ability to rapidly predict the flow environment (a CFD challenge – dynamic grid adaptation; highly efficient solvers for 3D transient mixed flows; workable turbulence models; PC-based parallel computing capability (~ 1000 PCs); and large database management & postprocessing technologies)
  - Interfacing CFD predicted flow environments and loads with stress and structural dynamics codes and material databases to determine part thickness, yield and failure limits, and margins of safety (dual challenge – CFD has to provide what stress needs, stress has to understand CFD's limitations and areas of uncertainty)
  - Acquiring quality test data and experiments to validate models and predictions

Conclusions, and

Some Thoughts on University, Government and Industry Collaboration

Conclusions

- **The future of Space Transportation is bright - strong markets in military, commercial, scientific applications will emerge in the next five years**
  - Reliability is essential but cost is and will be the discriminator (both non-recurring and recurring costs will be considered)
  - The next generation Reusable Launch Vehicles (shuttle replacements) will fly in the 2012 – 2020 time frame
  - The Military Aerospace Plane may the next big space program
  - Global competition will intensify especially in the commercial market
- **Future development programs will rely heavily on system level thinking, robust design principles, multidisciplinary analysis and optimization, and on the use of high fidelity predictive tools even in the conceptual design cycle**
- **Development testing will be significantly reduced in favor of large scale, high fidelity simulations and virtual engineering practices**

Some Thoughts on Collaboration between Universities, Government & Industry

- **Closer collaboration between Industry, Government & Universities is essential if US is to maintain its edge in the global market place in Space Transportation**
  - Industry – Technology needs, direction & focus, engineering insight & hardware knowledge, jobs and internship opportunities
  - Government – Funding and program oversight, facilities (especially test), specialized technical expertise, university grants, jobs
  - Universities – Creativity & “out-of-the-box” thinking, fundamental & applied research, technical expertise, the next generation scientists and engineers